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THE USE OF RADAR IN FLASH FLOOD FORECASTING

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ABSTRACT

The accuracies of the present raingage density and WSR-57 radar measured rainfall are statistically examined. It is shown that radar can assess areal rainfall in shower type precipitation significantly better than the present raingage density.

The results of correlation studies between a dense network of raingages in Oklahoma (175 recording raingages in 1100 mi.^{2}) and the WSR-57 located at Norman, Oklahoma are shown. Also, an operational method of semi-automatically processing the voluminous radar data, in REAL-TIME, in an applied radar hydrology experiment is discussed. The results of correlating the radar measured rainfall with stream flow are shown.

I INTRODUCTION

It has long been recognized by hydrologists that the most uncertain parameter which is used as an input to flash flood warning and flood forecasting techniques is rainfall rate and/or accumulation. Several sources contribute to uncertainty of the rainfall data: (1) rain gage density, (2) raingage inaccuracies, and (3) communications.... These inherent raingage problem sources pointedly show the need for a more refined rain-gaging instrumentation -- instrumentation that will reduce the sampling errors to within acceptable limits.

Today radar is the only instrument available that is capable of qualitatively and quantitatively observing precipitation over large areas on a nearly continuous basis. However, the operational use of radar data to assess areal rainfall has lagged. The predominate reasons for this lag is the variable nature of the relationship between precipitation rates and the radar reflectivity factor Z. Also, how to numerically analyze and communicate the voluminous amount of radar data in REAL TIME. These problems and their partial solution are discussed in this paper. It is, also, statistically shown that the accuracy of a standard WSR-57 10-cm radar's measurement of areal rainfall is generally better than the present raingage density measurements.

The methodology and results of an experiment in applied radar hydrology between the River Forecast Center, Ft. Worth, Texas, the River Forecast Center, Tulsa, Oklahoma, National Severe Storm Laboratory, and Greater Southwest Air-port, Fort Worth, Texas are discussed. A radar-computer program was used to estimate areal rainfall and the results compared with observed rainfall runoff values.

The WSR-57 is referred to in all discussions of radars.

II RAINGAGE ASSESSMENT OF AREAL RAINFALL

Accurate forecasting of floods depends to a large extent on knowing the amount of precipitation falling over a given area, but areal precipitation is one of the most questionable parameters used.

A. Rain Gage density and statistical sampling.

Rain gage spacing is by far the largest contributor to the uncertainty of the rainfall data. The average density of raingages in the U.S. is about one gage in 230 square miles (1). But this average varies from a density of one gage in 55 square miles in Connecticut to one gage in several thousand square miles in West Texas. Therefore, an 8-inch raingage whose area is about 1/80 millionth part of a square mile must be assumed to represent the rainfall over areas as large as 230 square miles, or, in the most dense rain gage network in Texas, about 625 square miles. With one gage in 625 square miles, the raingage is sampling about 1/50 billionth part of the area.

Considering that the intense part of most thunderstorms is 5 to 10 miles in diameter or an area of 4 to 8 square miles, the probability of a raingage sampling this intense part is 1/10 billionth, yet this intense part contributes about 80% of the total rainfall. Ordinarily the raingage is sampling the lighter portions of the individual thunderstorms. The hydrologist is mainly interested in the areal average rainfall, and his only means at present is using the observed raingage values and inferring the average from this sparse data. Consequently, his educated guess is generally too low.

The variable nature of shower type precipitation dictates that many measurements be taken to yield an estimate of areal average. Most investigations of the variance of rainfall with distance from the center of maximum rainfall shows a paraboloidal distribution, the variance is an inverse exponential function of distance from the maximum rainfall (2).

According to experimental studies conducted by J. C. Neill (3) in Illinois, for a one-inch mean rainfall and gage density of one in 96 square miles, the population mean rainfall lies in the 95% confidence interval of .45-1.55 inches or ± 55%. This deviation undoubtedly increases as the area represented by each gage increases.

As one solution to the paucity of raingages, many people have advocated a greater gage density, but unless the raingages were very dense this would not solve the problem of statistical sampling, especially in showers. Further, such a density of raingages would certainly be economically unfeasible.

B. Raingage catch inaccuracies.

The accuracies of raingages varies according to location, meteorological parameters, exposure and numerous other factors. The effects of wind are meteorologically most significant. Some experiments have shown that the deficiency of a raingage catch increases about 10% for each 10 knots of wind (1).

C. Rainfall reporting.

Communications are a constant problem in storm areas, especially where the principle method of communications is by telephone. Frequently, critically needed rainfall data are delayed in transmission to River Forecast Centers and River District Offices because of telephone equipment outages due to storm damage.

Observing errors in both amounts and timing frequently occur. Unless it is a recording raingage, no accurate assessment can be made of these errors.

This highlights the problem of raingage representativeness that has always plagued hydrologists. As has been shown, raingages alone are often misleading with regard to the total average accumulated rainfall over an area, especially when shower type precipitation occurs.

III HYDROLOGY OF STORMS

The associated problems in ascertaining the areal average rainfall are:

1. Distribution of rainfall.
   a) Was it an even distribution or did some parts of a river basin receive decidedly more rainfall than other parts?
2. Time distribution of rainfall.
   a) Intensity - Did the major portion of the rain fall in: 1 hour, 6 hours, or how long?
3. Direction and speed of movement.
   a) Did the storm move upstream, downstream, or across the basin?

The hydrologist needs to know all three of these to calculate the volume of runoff and its time distribution. It is this volume distribution that determines the flash flood or flood potential of a storm.

Definition of a potential flash flood area - The term is applied to any small stream with a small drainage area, to that part of the upper reaches of any river in which sudden rises can be caused by locally heavy downpours or heavy showers, and are characterized by the fact that time necessary to form a peak wave in less than 24 hours.

The areal and temporal distribution of rainfall are self explanatory, but the speed and direction of movement of a severe thunderstorm is of equal importance in its flash flood potential.

1. Any time an intense storm is stationed over a flash flood area for a prolonged period of time a potential flash flood situation exists. The time period is an inverse relation of the intensity.

2. If a storm is moving perpendicularly or across a basin at moderate speeds the flash flooding potential is lessened, but if the storm is a slow moving system and other systems are building in behind the flash flood potential increases sharply.

3. A thunderstorm system moving upstream at moderate speeds can produce flash flooding in small areas, but over areas large with respect to the storm's dimensions will generally produce a moderately rising stream.

4. An intense storm system moving downstream has real flash flood potential and should be observed closely.

Several hydrologic aspects of intense storms that can contribute to flash flooding or even major flooding have been mentioned, but for the most part this is information the raingage cannot give. The synoptic station and local forecaster can help some in these areas, but he is limited to probability forecasting of rainfall events.

IV RADAR RAINFALL MEASUREMENTS

Because of radar's ability to observe precipitation in the atmosphere almost continuously in space and time, efforts have been made since World War II to relate the radar echoes' intensity to precipitation rate and/or accumulation.

A. Radar Theoretical Discussion

Ryde, in 1945 (4), applied Gustav Mie's scattering theory for the back-scattering cross-section of a spherical drop to the study of radar echoes from water and ice particles. He showed the back-scattering cross-section of a single particle was:

(1) $$\sigma_i = \frac{64\pi^5}{\lambda^4} |K|^2 A_i^6$$

where $K = (m^2-1)/(m^2+2)$ the complex index of refraction, λ is the wave length, "A" is drop radius. This equation is very similar to the Rayleigh scattering formula and is usually referred to as the "Rayleigh approximation". When the drop diameter is less than about .04 λ, the approximation can be used without correction. Otherwise the more complex Mie formula must be used.

Marshall, Longille, and Palmer (5) were among the pioneers in the investigation of measurements of precipitation by radar. They reported in their study that the average power reflected from precipitation was proportional to the summation of the back-scattering cross-sections.

(2) $$\overline{P}_r = \frac{P_t A e}{8\pi r^2} h \sum_{vol} \sigma_i$$

$\overline{P}_r$ = average power received

P_t = peak transmitted power

h = Pulse length (WSR-57 long Pulse = 4 Msec)

Ae = effective cross-sectional area of the antenna

σ = back-scattering cross-section of a particle

r = range

Making use of Ryde's back-scattering formula, Ap the apertual area of a paraboloidal antenna, and the gain G of a highly directional antenna, Battan (6) lists a slightly more usuable form of the equation:

$$(3) \qquad \overline{P}_r = \frac{8\pi^5}{9}\left(\frac{P\ \theta\ \phi\ h\ Ap^2}{\lambda^6}\right)\frac{|K|^2}{r^2}\sum_{vol} A_i^{\,6}$$

θ, ϕ = horizontal and vertical radar beam dimensions (radians)
λ = wave length (WSR-57 = 10 cm)
A_i = drop radius (mm)

Nowadays it is a common practice to specify drop sizes in terms of their diameters, thus: (4) $\overline{P}_r = P_t \left(\frac{\pi^5 \theta\ \phi\ Ap^2}{72\lambda^6}\ |K|^2\right)\frac{\sum_{vol} ND_i^{\,6}}{r^2}$

The symbol Z is used to designate $\sum ND_i^{\,6}$, and is called the reflectivity factor. The radar parameters in parenthesis are constants for a particular radar, therefore; (5) $\overline{P}_r = \frac{P_t\ C\ Z}{r^2}$ or $Z = \frac{\overline{P}_r}{P_t}\ \frac{r^2}{C}$

It is assumed in this equation that:

(1) All radiated energy is confined to the cone defined by θ and ϕ (half-power points).

(2) The radar beam is completely filled with precipitation (r^2Vsr^4).

(3) The average returned power is measured.

(4) No attenuation of the radar signal.

(5) The diameters of scattering particles are small in relation to the wave length ($D \leq .04\ \lambda$).

The r^2 term is accounted for electronically in the WSR-57.

B. Raindrop size distribution and the Z-R relationship.

Many investigators in a variety of places and in various types of precipitation have made measurements of raindrops recorded on dyed filter paper for statistical correlation with precipitation intensity.

In 1948 Marshall and Palmer (7) studied the distribution of raindrops with size. They found an inverse exponential distribution for the number N of raindrops per unit size range in unit volume of air. The distribution they proposed was in fair agreement with earlier investigators, Laws and Parsons (8), and others.

Except at diameters less than about 1.5 mm, the experimental data can be fitted by the equation:

$$(6) \qquad N_D = N_o e^{-\Lambda D}$$

where D is drop diameter, $N_D \Delta D$ is the number of drops of diameter D between D and $D+\Delta D$. N_o is the value of N_D for D = 0, also, N_o = .08 cm-4 for any intensity of rainfall, and $\Lambda = 41R^{-0.21}\text{cm}^{-1}$ = slope of line when the distribution is plotted on semi-log paper for a given rainfall rate.

R is the rate of rainfall in mm hr^{-1}. It will be noted that different distribution exists for different rainfall rates.

$$\text{Then:} \quad Z = \sum N_D D_i^6 = \int_0^\infty N_o e^{-\Lambda D} D^6 dD = \frac{N_o \Gamma(7)}{\Lambda^7}$$

$$\text{Note:} \quad \int_0^\infty e^{-x} x^n dx = \Gamma(N+1) = N!$$

$$\Gamma(7) = 6! = 720$$

considering rainfall rate is given by:

$$(8) \qquad R = \sum \frac{\pi \rho}{6} N_D V D^3$$

where V is the terminal velocity of drops of diameter D, ρ is the density of water, and near the ground the vertical air speed is assumed to be quite small.

The drop diameter has been empirically related to the fall velocity by

$$(9) \qquad V = 130D^{\frac{1}{2}}$$

Therefore:

$$(10) \qquad R = \int_0^\infty (N_o e^{-\Lambda D}) \left(\frac{\pi}{6} \rho D^3\right) (130D^{\frac{1}{2}})\, dD$$

integration of (10) yields

$$(11) \qquad R = \frac{130}{6} \pi \rho N_o \frac{\Gamma(9/2)}{\Lambda^{9/2}}$$

<u>note</u>: $\frac{1}{2}! = \frac{\sqrt{\pi}}{2}$

combining this equation with (7) gives:

(8) $$Z = 1.6 \times 10^6 \frac{R^{14/9}}{N_o^{5/9}}$$

or

(9) $$Z = 210R^{14/9} \text{ mm}^6\text{m}^{-3}$$, where R is in mm hr^{-1}

Since Marshall and Palmer, many investigators (6) have studied the empirical relation between the radar reflectivity factor Z and precipitation rate R with all reporting equations of the form;

(10) $$Z = aR^b$$

where "a" is related to drop size spectrum and "b" is related to the fall velocities. Some of these relationships have been listed by Battan ((6) Table 7).

A slight revision of the equation originally proposed by Marshall and Palmer (7) is considered to be representative of most rains and is universally accepted is:

(11) $$Z = 200R^{1.6}$$

C. Accuracy of radar rainfall measurements.

Battan (6) has suggested that a different Z-R relationship be used for different rain types and different geographical locations. This is supported in a paper by Atlas and Chmela (9). Wilson (10) notes that values of "a" and "b" are often stable within storms, but that significant variations occur from storm to storm.

A plot of Z-R relationships listed in Battan (6) shows most of the relationships are within about a factor of two of each other. Marshal et al.(5) expressed the opinion that, for a given value of Z, the error of estimate of R is about a factor of 2, using $Z = 200 R^{1.6}$. Using this equation has led most investigators since, to the conclusion that radar can estimate areal and time integrated rainfall within a factor of ± 50% of the true mean areal rainfall as determined from point raingage measurements.

In 1964 (11) and 1965, while the author was at the National Severe Storms Laboratory (NSSL), the WSR-57 radar observations on eight days with intense convective rains were compared with 175 recording raingages spread over 1100 square mile area within 55 n.m. of the radar (fig. 1). The relationship $Z = 200\ R^{1.6}$ was to estimate the radar echoes' rainfall equivalent (fig. 1 and 2) for all storms.

The radar estimated average rainfall for seven storms varied by less than ± 50% from the raingage average rainfall (fig. 2). It is suspected that the radar calibration was in error for the storm of 5/24/65.

As a general rule, the radar results improved as temporal and spatial distribution of precipitation increases.

The variability between raingage average values could be due to many factors: (1) drop-size distribution, (2) Possible overshooting, (3) Beam filling, (4) Growth or evaporation of rain drops below the radar beam, (5) effective fall velocities, (6) radar beam characteristics, and (7) Digitizing methods. But the author believes one of the largest contributors to the difference between radar estimated rainfall and the raingage values lies in the differences of the respective volumes sampled. At 50 n.m. the radar is interrogating a horizontal cross sectional area of about one square mile, while an 8-inch raingage is sampling about 1/80 millionth part of a square mile. Further, the NSSL radar data were digitized in grid squares 2.5 n.m. on a side, or 6.25 square miles, raingage would be sampling 1/500 millionth part of this area.

Indeed, the radar-rain gage correlations are amazing, considering the percent of the population sampled with the raingage.

V AN EXPERIMENT IN APPLIED RADAR HYDROLOGY

A. Introduction.

The largest problem that presents itself is how to numerically analyze and automatically process the large volume of radar data that is available with each scan of the antenna, in REAL TIME.[1]

A very interesting operational experiment in the digitization and communication of radar data in REAL TIME was carried on in 1965 between the National Severe Storms Laboratory (NSSL) WSR-57 radar, the River Forecast Center at Fort Worth, Texas. (RFC, FTW), and the River Forecast Center at Tulsa, Oklahoma (RFC, TUL), and this spring (1966), Greater Southwest Airport (GSW) WSR-57 radar was included in the experiment. (Figure 3.) They jointly evaluated means for using digitized radar data in operational hydrologic analysis.

Every 30 minutes the radar operation branches of NSSL and GSW collected echo intensity data and transferred it, in digital form, to the RFC FTW (fig. 4 top). The RFC FTW computer processed the echo intensities for precipitation rate, accumulated precipitation, and the motion of the precipitation's center of mass. Radar estimated accumulated storm precipitation was transmitted to RFC TUL for use in preparing hydrologic forecasts (fig. 4 and 5).

The objectives of this project were:

1. Evaluation of a method for transmitting quantitized WSR-57 radar data to an operational computer facility, and
2. Evaluation of the usefulness of computer-processed WSR-57 radar data

[1] REAL TIME is a time lag of 30 minutes or less to a River Forecast Center.

as input to the RFC forecasting system.

The only major modifications made to the radars for this experiment were the installation of signal integration and contouring circuits developed by Dr. Lhermitte at NSSL (12). These circuits assure measurements of the average return power within $\pm$ .5 db.

Using the integration circuits, 5 levels of echo intensity can be displayed at one time, 10 db apart. These values can be easily changed to Z values, because $\Delta Z = 10^{\frac{\Delta db}{10}}$. (See Figure 10).

B. Radar Data Digitization and Transmission

The contoured log Z values were hand digitized and transmitted ($\log Z = \log 10^2 = 2 \log 10 = 2$) (fig. 4) in REAL TIME by facsimile and teletype to the Fort Worth River Forecast Center's 1620 computer. The scale of the rectangular grid reference map used for digitizing was determined by the width and line spacing of the M-28 teleprinter standard carriage. The horizontal grid size is identical to the key spacing, and vertical grid size is matched to the line spacing. The grid array is 60 x 36. When adjusted to a 100 n.m. scope display, grid rectangles are 5.55 x 3.34 n.m. or 18.5 square miles.

Using this scale, the radar meteorologist can insert the radar scope tracing of contoured log Z values into the teleprinter and cut a teletype tape by overpunching the integers. The overpunching, also, contributes to quality control of the radar data before transmittal to the RFC FTW.

C. Radar Data Processing.

The FTW RFC, using the 1620 computer and the equation $Z = 200 R^{1.6}$, converted the log Z values to rainfall rates (figs. 4, 5, 6 and 7).

An additional computer program was used that found the centroid positions of successive radar echo patterns. Then the rainfall distributions were moved over the vectored path connecting the centroid positions. This enabled the computer to integrate the computed rainfall (figure 8).

The rainfall data was accumulated for points and also was averaged for selected river sub-basins (figure 9). This information was relayed to TUL RFC by teleprinter.

D. Radar-Raingage-Streamflow Data Comparisons

Linear regression analysis by least squares were made for storms of 5/18/65 and 5/27/65 by RFC TUL. Comparisons were made of the radar-computed rainfall and the areal rainfall derived by isohyetal analysis of observed rainfall. Results of these analyses by storm total and by classes are shown in Table I below.

TABLE I

Storm	Class	No. Cases	Average Observed Rainfall Inches	Average Radar Rainfall Inches	Standard Error of Estimated Inches
May 18, 1965	Total Storms	130	0.37	0.34	0.33
	0 to 0.29 inches	75	0.10	0.17	0.18
	0.30 to 0.60 inches	25	0.46	0.40	0.27
	0.61 to 0.90 inches	11	0.77	0.75	0.47
	0.91 to + inches	19	1.16	0.79	0.48
May 27-28, 1965	Total Storms	166	0.30	0.30	0.21
	0 to 0.29 inches	94	0.11	0.17	0.13
	0.30 to 0.60 inches	46	0.43	0.45	0.23
	0.61 to 0.90 inches	21	0.74	0.54	0.62
	0.91 to + inches	5	1.02	0.43	0.47

Stream gage records furnished by the U.S.G.S. office at Oklahoma City were analyzed for runoff volumes produced by the two storms. The results of these analyses are shown in Table II.

TABLE II

Station		Average Observed Rainfall Inches	Average Radar Rainfall Inches	Rainfall Needed to Produce Observed Runoff Inches
Deep Red Run	@ Randlett	0.48	0.48	*
Cobb Creek	@ Ft. Cobb	0.92	0.92	*
Rush Creek	@Mansville	0.55	0.57	0.40
Little River	@ Sawakwa	0.41	0.40	0.60
Canadian River	@ Noble	0.56	0.57	0.21
Turkey Creek	@ Drummond	0.12	0.20	0.12
Little Washita	@ Ninnekah	0.48	0.59	*
Washita	@ Carnegie	0.65	0.72	*
N. Canadian River	@ El Reno	0.28	0.20	*

* No runoff forecasted or observed.

The average rainfall depths for the contributing zones are tabulated for observed and radar-rainfall. The third column lists the rainfall needed to produce the observed runoff depth.

E. Radar Hydrology Experiment Summary.

Note the remarkable agreement between observed and radar rainfall columns. Since the 1965 sample was quite small, no statistical significance should be attached at this time. However the results do indicate that this line of attack on the problem of precipitation measurements by radar should be continued. Additional radar data was collected this spring (1966) for similar correlation studies. Preliminary analysis indicates the correlations are compatible with the 1965 results.

Future reports on this experiment will be forthcoming as data and results warrant.

VI CONCLUSION

The standard WSR-57 10-cm radar can survey out to a hydrologic range of 100 n.m., or over 31,000 square miles, almost continuously. Such an area will generally contain about 40 to 50 raingages, but the radar will survey about 28,000 discrete points.

The potential quantitative value of radar as a direct raingaging instrument is assessed in the relationship between radar echo intensity and precipitation.

It was shown, using the relationship $Z = 200 R^{1.6}$, the radar will estimate the areal average rainfall within a factor of $\pm$ 2 of the areal average rainfall. Comparisons of radar average rainfall with a dense network of raingages in Oklahoma showed the radar could estimate the true mean within $\pm$ 50%. In 1961, Liber, Merritt, and Robertson (13) showed for a 24-hr storm over a tri-state area the radar average was within 2% of the actual rainfall average. While perhaps this result was fortuitous, it has been shown the radar results will improve as the temporal and spatial distribution increases.

One raingage in 100 square miles estimates the true mean rainfall within a factor of about $\pm$ 55% for a one-inch rainfall. The average gage density in the U.S. is one in 230 square miles, and in Texas it is about one in 625 square miles. Therefore, one can reasonably expect the standard error of estimate of true rainfall to be a factor somewhat greater than 2. Indeed, shower type precipitation (11) measured by a dense network of raingages in Oklahoma, one gage for 6.25 square miles, showed the sample's standard error of estimate about equal to the sample mean.

It is concluded the WSR-57 is a better raingaging instrument than the present raingage density, especially, for shower type precipitation. Not only does the radar measure the areal rainfall by a factor somewhat smaller than 2, and its time distribution, but also the speed and direction of major storm movement which contributes greatly to the assessment of flash flood potential.

The applied radar hydrology experiment between RFC FTW, RFC TUL, NSSL and GSW demonstrated the capabilities of operational staff's to digitize, communicate, and computer process radar data in REAL TIME. This was an unique experiment, since the log Z values of the actual observed radar echoes' intensities were digitized and transmitted to a computer center in REAL TIME.

The analysis of the computer processed radar data by RFC TUL showed remarkable results when compared with observed runoff. Also, this was an unique analysis because it was the first time radar data had ever been correlated with runoff. Whether the results they obtained were fortuitous will be determined when more data becomes available for analysis. This analysis does point out that correlation studies between runoff volume and radar estimated rainfall are probably more hydrologically realistic than between point rainfall areal averages, with the present raingage density, and radar estimated rainfall. In this study, the observed point rainfalls are representative of only 1.7×10^{-9} part of the area of rainfall observed by radar for the 18.5 square mile areas. The statistical reliability of such a small sample is dependent upon the meteorological process involved. Most of the storms studies in this experiment were thunderstorms with highly variable distributions of rainfall over the area.

This experiment, also, shows the operational radar meteorologist the possibilities of assessing the flash flood or major flood potential of radar echoes with the tools available to him; (1) WSR-57 radar (calibrated daily when possible), (2) Workable size grid, (3) Rainfall - echoe intensity chart using $Z = 200R^{1.6}$, and (4) judicious selection of radar intensity levels that will assure measurements of the most intense parts of the echo.

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<u>FIGURES</u>

1. Network of 175 surface recording raingages maintained by the Agricultural Research Service, Chickasha, Oklahoma.

2. Raingage-radar average rainfall comparisons for the dense network of raingages in Oklahoma.

3. Map of radar coverage for NSSL's and GSW's WSR-57 radars.

4. <u>Top figure</u> is the teleprinter overpunch of traced radar contours reflectivity integers (log Z)

   <u>Bottom figure</u> is digitized map of accumulated precipitation as computed by RFC FTW computer for operational transmission to the RFC TUL. The number at the top is the multiplier for the integers (.8755 x 5 = 4.38 inches).

5. Visual display of radar-rainfall data for technical evaluation as provided by the 1620 computer.

6. Visual display of observed rainfall data as provided by 1620 computer from rainfall data punched on IBM cards.

7. Isohyetal maps of observed rainfall and radar rainfall. The printouts are provided by the 1620 computer.

8. (A) The radar rainfall equivalent for successive observations are averaged for application to the entire time period between observations.

   (B) The radar rainfall equivalent for successive observations are averaged at the mean centroid position and distributed over the vectored path connecting the observations and the mean centroid positions.

   (C) The centroid positions of the preceding and succeeding observations were used to vector each echo precipitation contribution in fifteen minute increments.

9. The radar rainfall averages by sub-basins. For computer identification the sub-basins were assigned numbers.

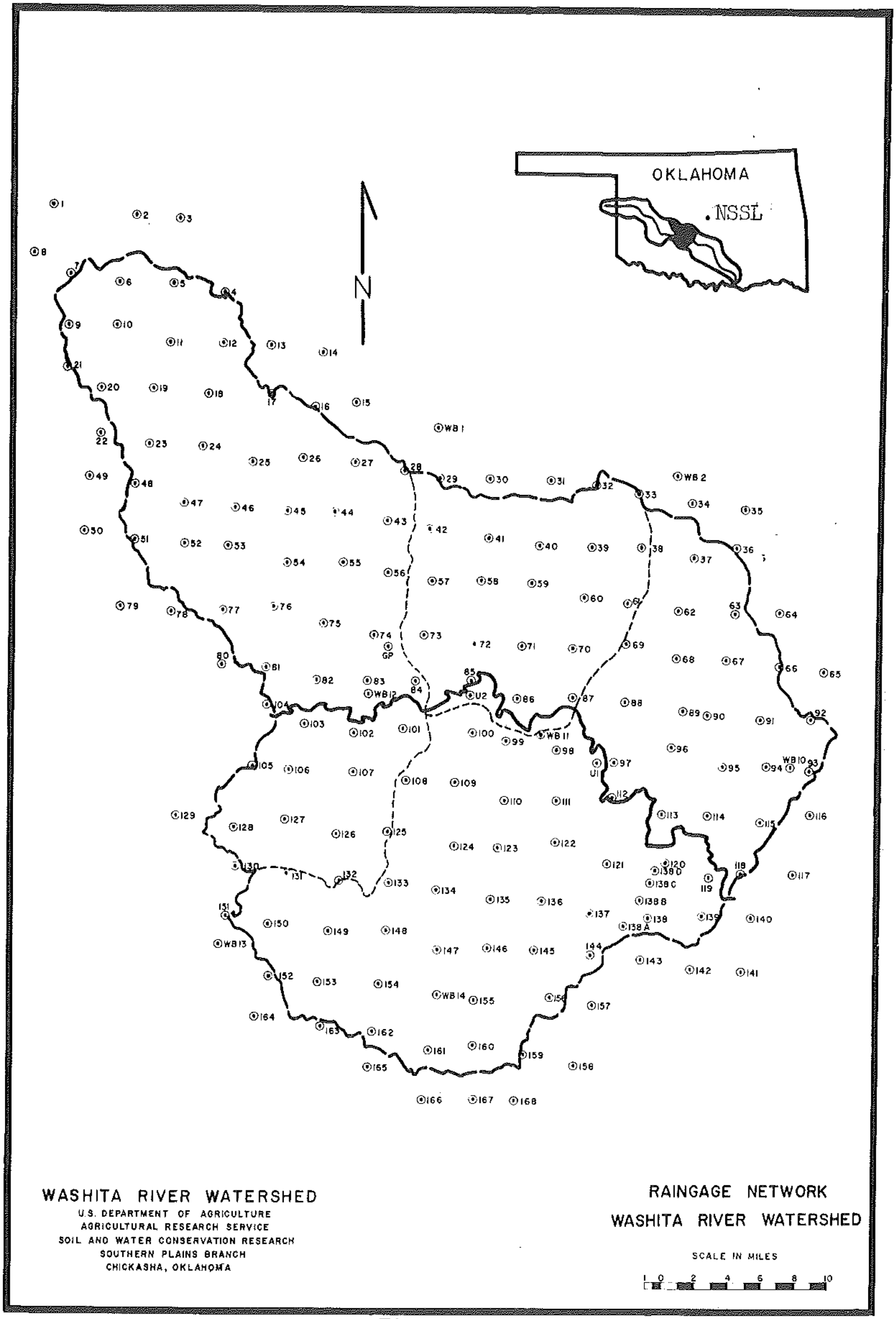

OKLAHOMA
.NSSL
N
WASHITA RIVER WATERSHED
U.S. DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE
SOIL AND WATER CONSERVATION RESEARCH
SOUTHERN PLAINS BRANCH
CHICKASHA, OKLAHOMA
RAINGAGE NETWORK
WASHITA RIVER WATERSHED
SCALE IN MILES
0 2 4 6 8 10

Figure 1

RADAR AND RAIN GAGE DATA

DATE	MDS	Rain Gage Average Rainfall	Radar Average Rainfall
4/3/64 1300-2000	-101	.20	.32
4/23/64 1700-1800	-107	.21	.41
5/9/64 1600-2400	-99	.92	.53
5/10/64	-102	1.09	.76
5/29/64 0000-2400	-106	1.67	1.33
5/30/64 0000-1700	-106	.83	.80
		2.50	2.13
5/13/65 1900-2300	-103	1.02	.78
5/24/65 1300-1600	-106	.15	.04

Figure 2

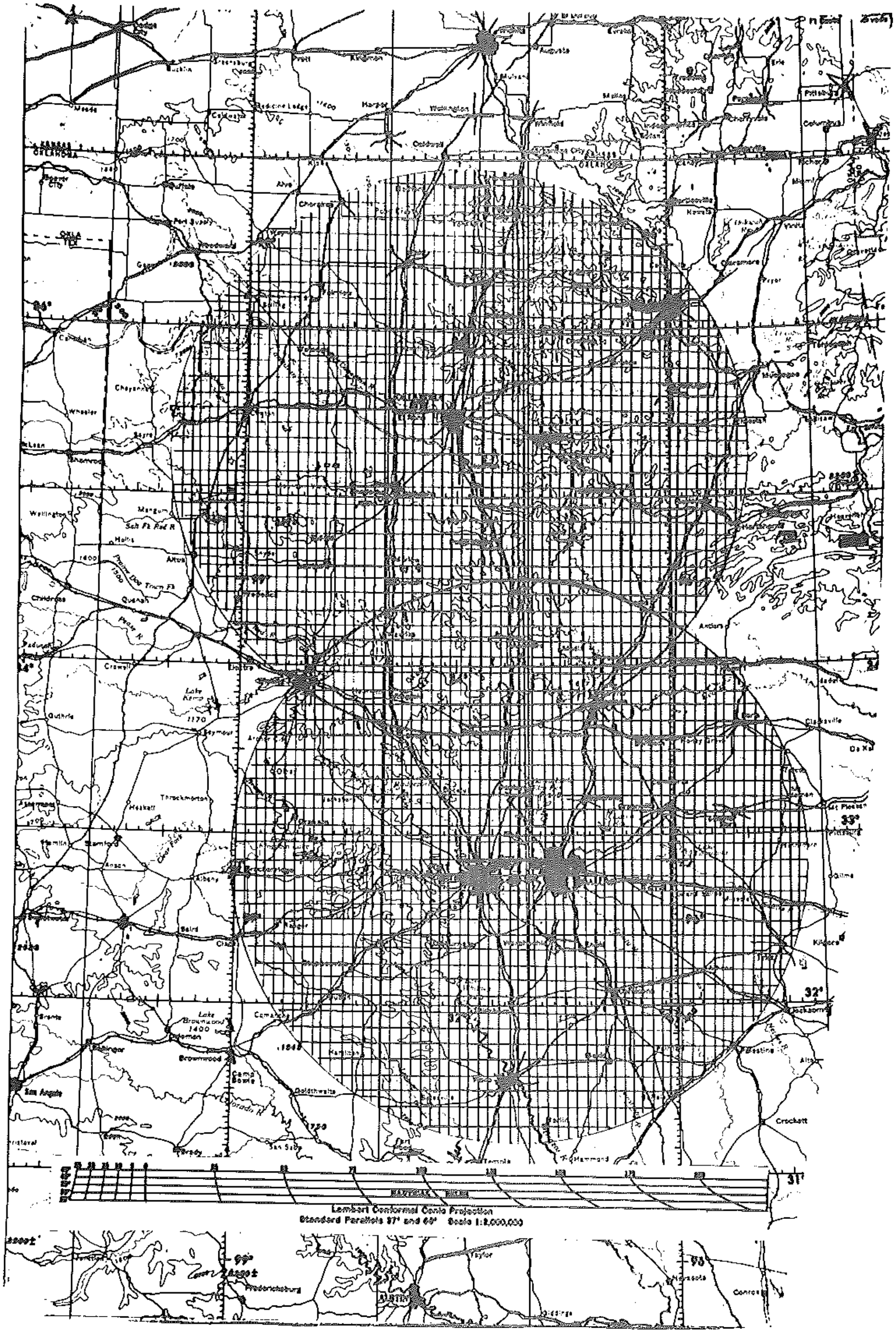

Lambert Conformal Conic Projection
Standard Parallels 37° and 65° Scale 1:2,000,000
Pratt
Kingman
Augusta
Wellington
Caldwell
KANSAS
OKLAHOMA
Alva
Cherokee
Woodward
Fort Supply
Cheyenne
Wheeler
Wellington
Mangum
Altus
Quanah
Childress
Crowell
Lake Kemp
Seymour
Throckmorton
Haskell
Stamford
Anson
Albany
Baird
Lake Brownwood
Brownwood
Camp Bowie
Goldthwaite
Comanche
San Angelo
San Saba
Brady
Hamilton
Temple
Clarksville
Jacksonville
Palestine
Crockett
Kilgore
Fredericksburg
AUSTIN
Taylor
Giddings
Conroe
Navasota
Fort Hammond

Figure 3

```
05271534C   05271604C   012016005
0000000000000000000000000000000000000000000000000000000000000
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0      12221                                                0
0     355332211                                             0
0     23332211                                              0
0      12221                                                0
0                                                           0
0                                                           0
0                                                           0
0                   11                                      0
0                 1111                                      0
01111       121111111                                       0
0 2221     12222111                                         0
0232221  1222222211                                         0
023332    23325532211                                       0
01221    2222353221                                         0
0                                                           0
0                                                           0
0000000000000000000000000000000000000000000000000000000000000
```

MOVEMENT FROM 270 DEG 006 KTS RELATIVE CHANGE IN INTENSITY 1.03

```
RAINFALL MAP
8755
0000000000000000000000000000000000000000000000000000000000000
0                                                           0
0                                                           0
0                                                           0
0                                                           0
0                                                           0
11                                                          0
0   1 1          1 1  1                                     0
22  1  111        11111                                     0
321 1111211    1      11      1                             0
1111 11 1 3 1  11     11      1                             0
0 111    1  111 11                                          0
0  11     111 1   1 1                                       0
0         11       1                                        0
0         1 111 11 1                                        0
0          111112 211111111           111111                0
0    1122121312145222232111111      11111111   1            0
0   1412342323144312354221 11      111112111111111          0
0 1 1211362773334574254111 1 3   11122112111111111  1       0
0  111111223434422356242111511   1 111242211111111111       0
0     3211 1111115542312111       111113221111  111111  1   0
0   11244112111114311123111      1111111111111              0
0     1111221521111114221 111 11111111111111111  11         0
0   1551121262123642242113211111111111121111111             0
0   1111212222124613                                        0
0   11112122221249613936156322531212111211111 11            1
014 1   1211241642115312431113321111131111111111111        11
111     11  1123341 21 1211112211111111111111111111         0
0       11  11221111    111111111211  11111111111111111     0
0       21111111 11111  1561112211111111111111111111111     0
0 111 1 11111111111111111155111112211111131111111111111     0
01111111111211112122111111 61123311211111111111111121111    0
1111121222211111121121122215111332221111111111111111111     0
11111311111252541211114121121112224111111111112121111       0
0  1  22 11115213343451113311225226111111 11 1111           0
0  1111 1    113222344444431111111112233211111 11           0
0       21         123434332111 111111  11111               0
0000000001000000000000000010000000011100010000000000001000000
```

Figure 4

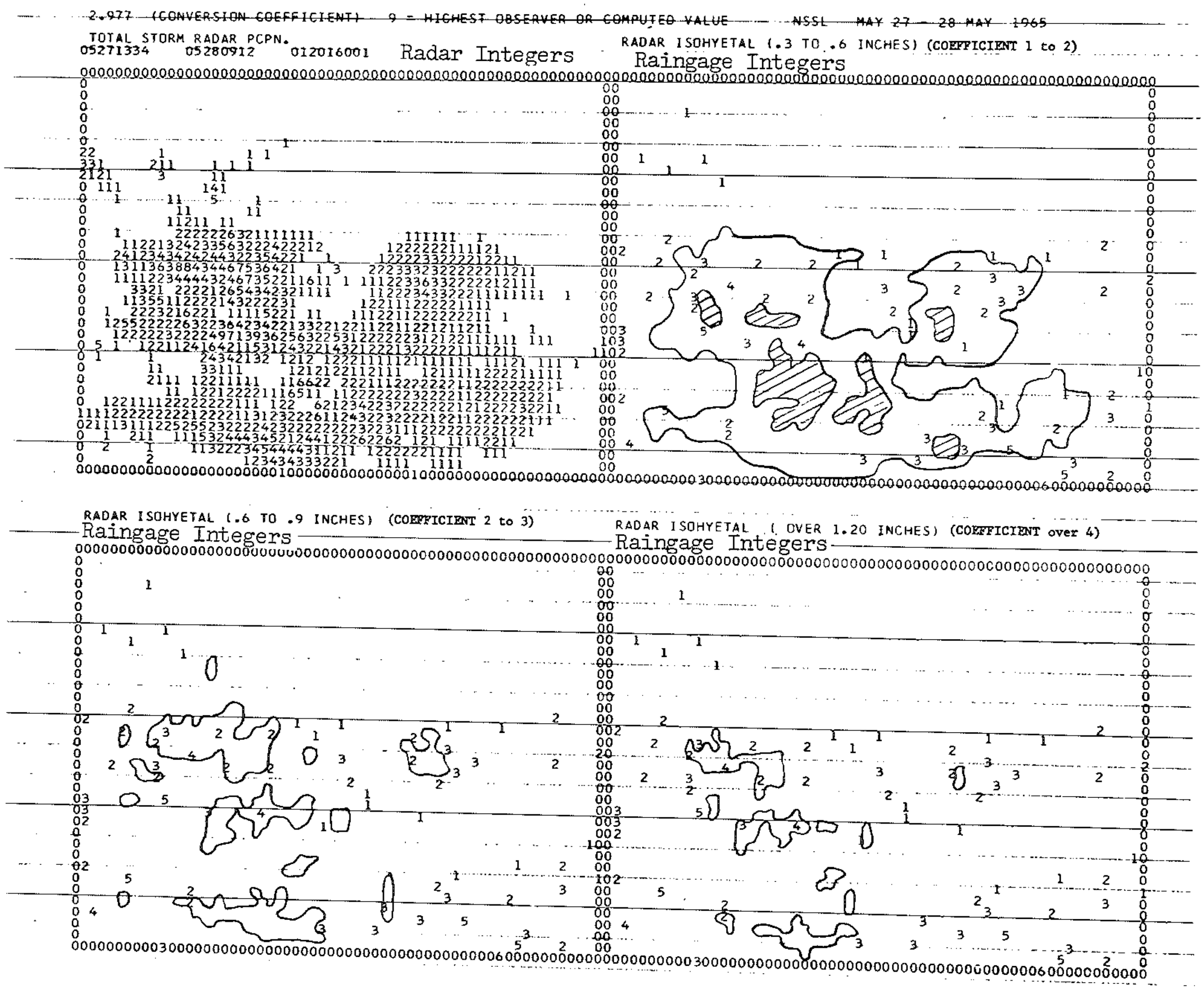
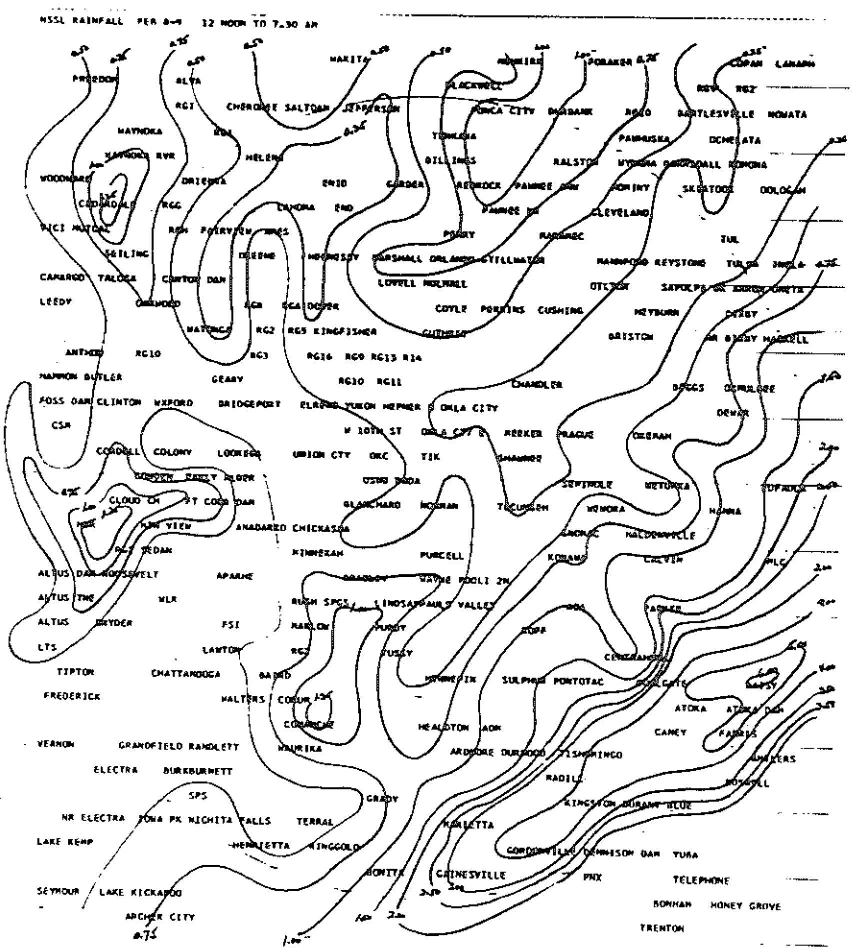

2.977 (CONVERSION COEFFICIENT) 9 = HIGHEST OBSERVER OR COMPUTED VALUE NSSL MAY 27 — 28 MAY 1965
TOTAL STORM RADAR PCPN.
05271334 05280912 012016001
Radar Integers
RADAR ISOHYETAL (.3 TO .6 INCHES) (COEFFICIENT 1 to 2)
Raingage Integers
RADAR ISOHYETAL (.6 TO .9 INCHES) (COEFFICIENT 2 to 3)
Raingage Integers
RADAR ISOHYETAL (OVER 1.20 INCHES) (COEFFICIENT over 4)
Raingage Integers

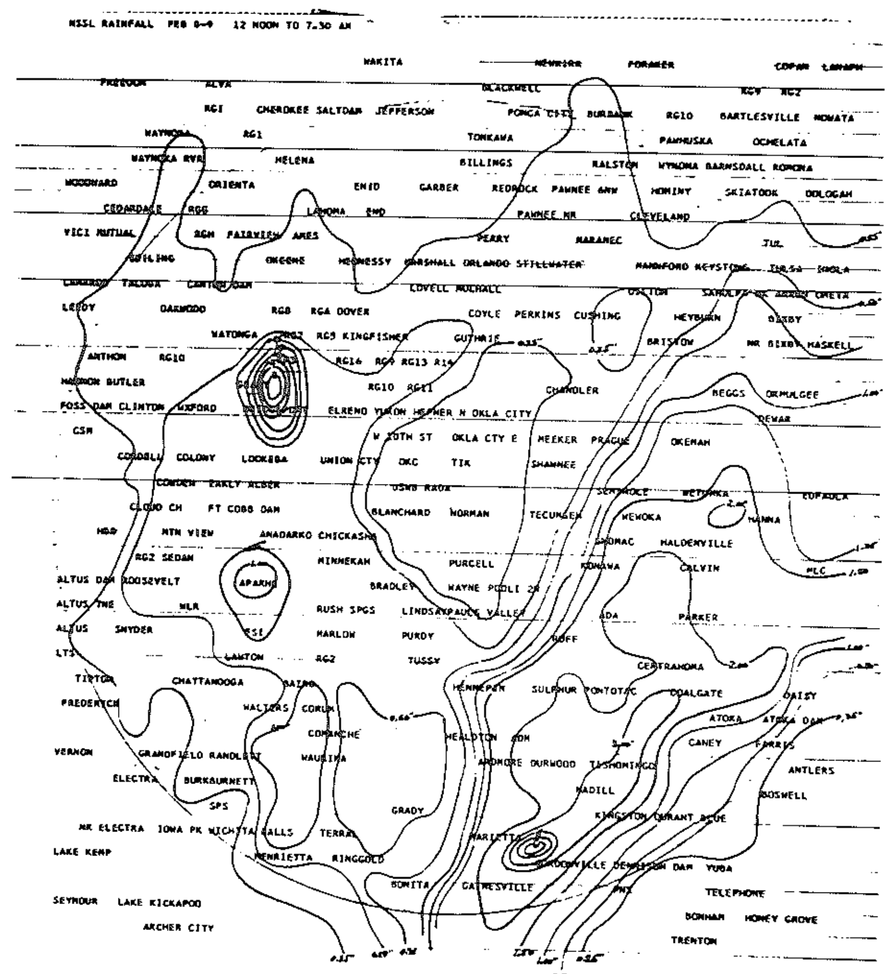
Figure 5

<u>Figure 6</u>

TULSA RAINFALL MAP MAY 27 – 28 1965

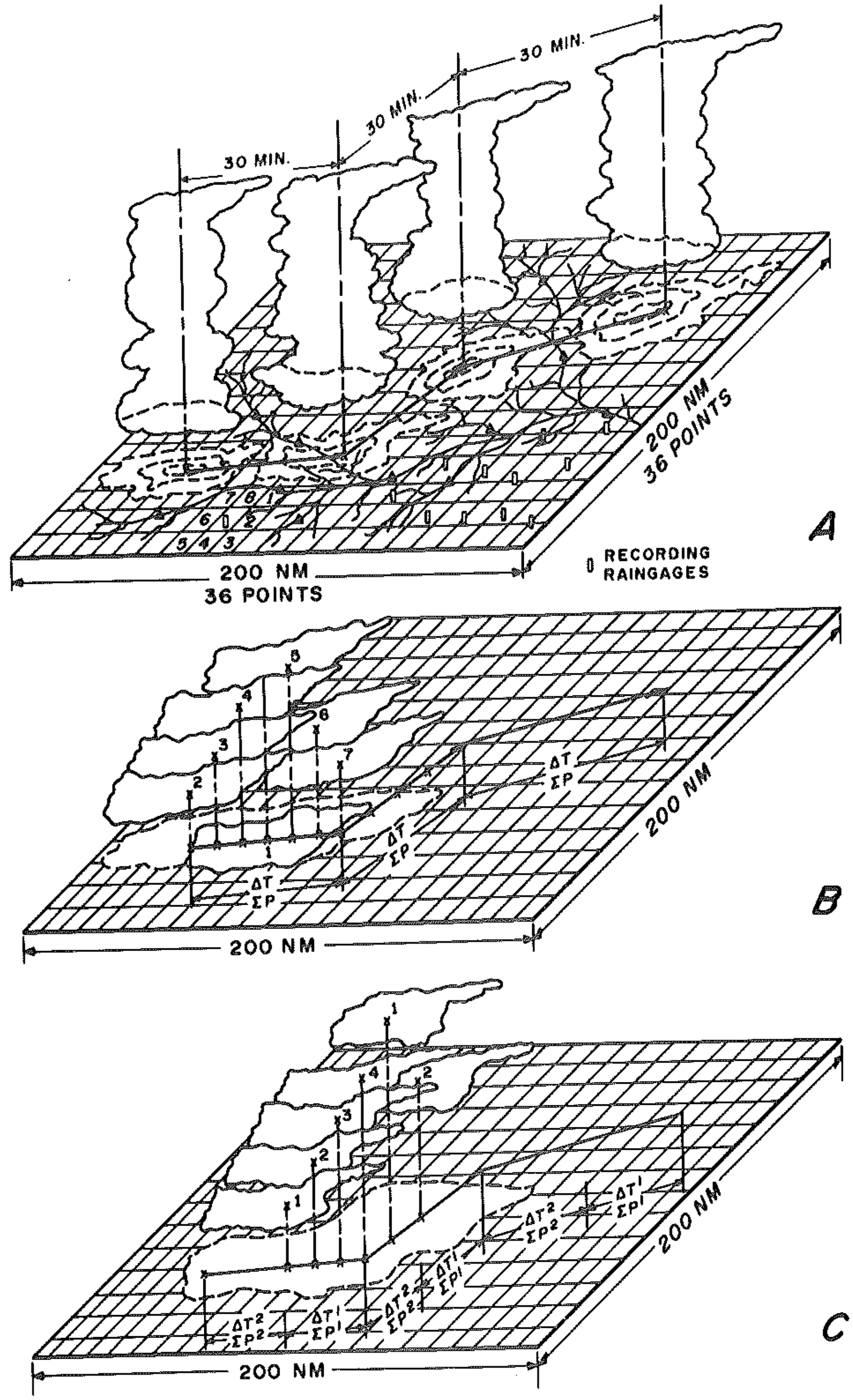


ISCHYETAL MAP - OBSERVED RAINFALL



ISOHYETAL MAP - RADAR RAINFALL

Figure 7



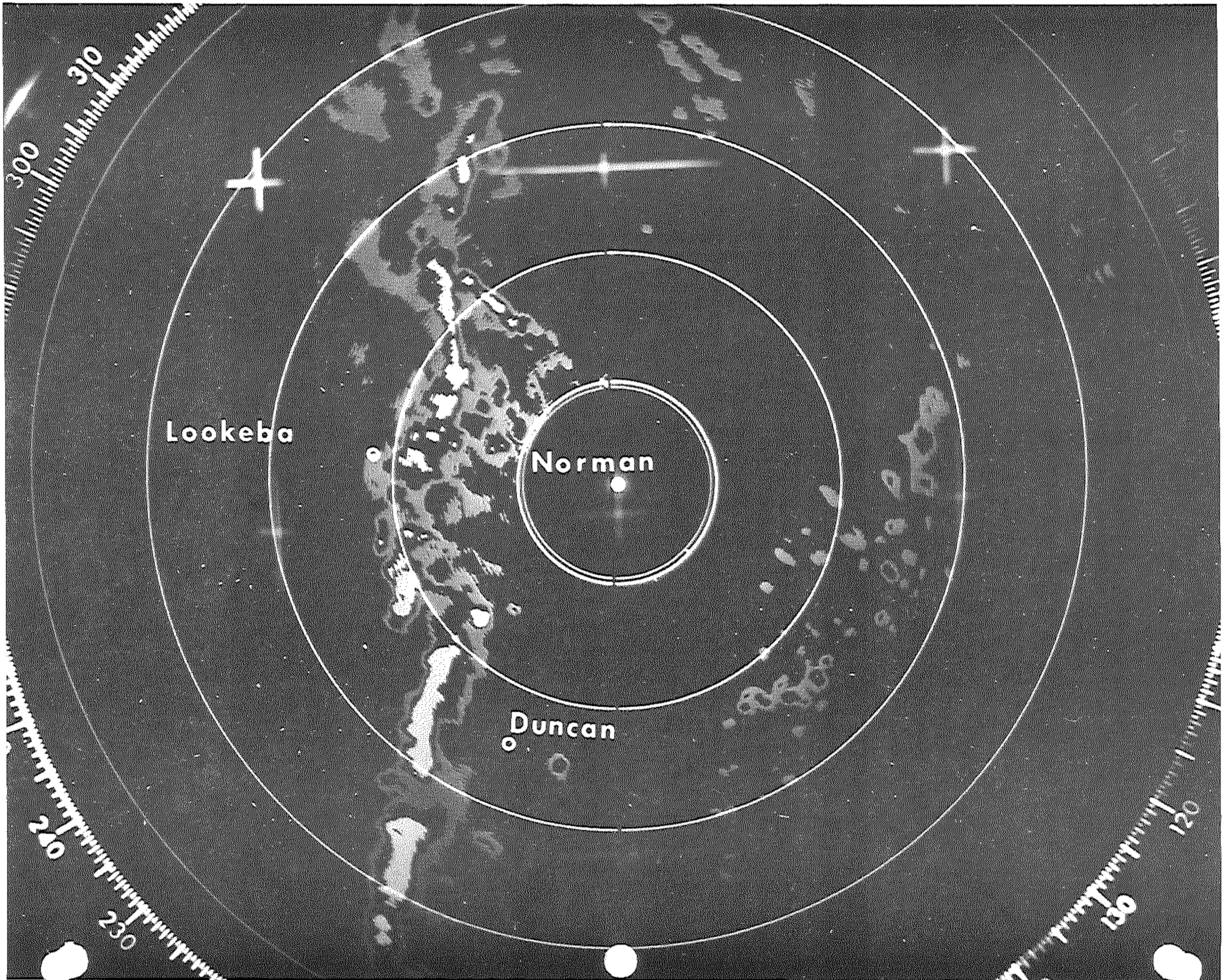
SCHEMATIC REPRESENTATION OF SPATIAL INTEGRATION TECHNIQUE

Figure 8

RADAR RAINFALL AVERAGES BY SUB-BASINS MAY 27- 28,1965

0001	049	0002	046	0003	069	0004	068	0005	059	0006	035
0007	084	0008	089	0009	096	0010	073	0011	084	0012	070
0013	026	0014	070	0015	029	0016	067	0017	046	0018	033
0019	055	0020	059	0021	117	0022	096	0023	092	0024	092
0025	039	0026	043	0027	037	0028	042	0029	015	0030	022
0031	107	0032	061	0033	066	0034	028	0035	042	0036	055
0037	079	0038	060	0039	049	0040	046	0041	065	0042	011
0043	010	0044	018	0045	022	0046	047	0047	040	0048	022
0049	050	0050	025	0051	039	0052	047	0053	048	0054	042
0055	040	0056	036	0057	033	0058	033	0059	040	0060	033
0061	062	0062	030	0063	007	0064	014	0065	015	0066	021
0067	021	0068	005	0069	009	0070	040	0071	059	0072	065
0073	025	0074	011	0075	050	0076	041	0077	046	0078	046
0079	036	0080	019	0081	031	0082	037	0083	004	0084	027
0085	020	0086	037	0087	050	0088	030	0090	019	0091	006
0092	007	0093	017	0094	000	0095	001	0096	001	0097	002
0098	000	0099	006	0100	000	0101	001	0102	000	0103	002
0104	003	0105	006	0106	012	0107	005	0108	000	0109	000
0110	000	0111	004	0112	005	0113	002	0114	000	0115	002
0116	005	0117	000	0118	000	0119	000	0120	000	0121	000
0122	000	0123	000	0124	000	0125	000	0126	000	0127	000
0128	000	0129	014	0130	015	0131	013	0132	013	0133	008
0134	015	0135	010	0136	015	0137	021	0138	026	0139	021
0140	017	0141	015	0142	024	0143	021	0144	010	0145	002
0146	001	0147	032	0148	030	0149	026	0150	021	0151	017
0152	024	0153	021	0154	024	0155	076	0156	034	0157	022
0158	017	0159	012	0162	021	0163	058	9900	035	9901	052
9902	031	9903	047	9904	064	9905	020	9906	014	9907	084
9902	031	9903	047	9904	064	9905	020	9906	014	9907	084

Figure 9



<u>Figure 10</u>